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Plug-in electric vehicles in electric distribution networks: A review of smart charging approaches

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ABSTRACT

Plug-in electric vehicles (PEV) are emerging as an efficient and sustainable alternative for private and public road transportation. From the point of view of electric grids, PEVs are currently considered as simple loads due to their low market penetration. However, as the PEV fleet grows, implementation of an intelligent management system will be necessary in order to avoid large capital expenditures in network reinforcements and negative effects on electric distribution networks, such as: voltage deviations, transformers and lines saturations, increase of electrical losses, etc. These issues may jeopardize the safety and reliability of the grid. As a consequence, this topic has been researched in many papers where a wide range of solutions have been proposed. This paper presents a review of different strategies, algorithms and methods to implement a smart charging control system. Also significant projects around the world about PEVs integration are presented. Finally, on the basis of this review, main findings and some recommendations are presented.

Contents

1. Introduction

Currently, transport sector faces significant challenges regarding the energetic model based on oil products. In fact, 62.3% of the oil consumed in the world in 2011 was due to the transport sector, which caused emissions of 6892 Mt of CO_2 into the environment [1]. This dependence and the excessive use of oil entails numerous issues: environmental problems such as climate change and pollution in large cities, economic problems due to rising oil prices and geopolitical problems due to the instability of the producing countries and oil use as economic weapon. In this scenario, plug-in hybrid electric vehicles (PHEVs) and electric vehicles (EVs), commonly referred to as plug-in electric vehicles (PEVs), could be a sustainable alternative to internal combustion

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engine vehicles. According to the U.S. Department of Energy, a PEV can be defined as a light vehicle that draws electricity from a battery with a capacity of at least 4 kW h and is capable of being charged from an external source [2]. Compared with conventional vehicles, PEVs present various advantages listed as follows:

- Reduces consumption of oil and decreases energy dependence from oil producing countries. Decreasing oil imports will improve the balance of payments of no producing countries.
- Reduces GHG emissions in function of electricity generation mix [3,4].
- Improves air quality in cities and, as a consequence, public health of citizens.
- Increases transport sector efficiency while the cost per kilometre is significantly lower than internal combustion engine vehicle (ICEV) [3].
- Can be charged from a wide range of different primary energy sources, adapting to the locally available energy sources.
- Could bring another set of advantages, due to the interaction between PEVs and the electric grid, such as: integration of more intermittent renewable energy resources (RES), improvement of the electric grid efficiency and reliability and decrease GHG intensity of the grid. Those advantages will depend on smart charging strategy used.

Table 1
Examples of commercial PEVs.

Model	Type	Battery capacity (kW h)	Electric range (EPA) (km)	Charge characteristics	
				Time (h)	Power (kW)
Mitsubishi iMiEV	BEV	16	100	7	3.1
Nissan Leaf	BEV	24	118	8	3.3
Tesla model S	BEV	60/85	335/425	8.5[a]	11[a]
Chevrolet volt	PHEV	16.5	61	3[b]	3.3
Toyota Prius	PHEV	5.2	18	1.5	3.3
Ford fusion energy	PHEV	7.5	34	2.5	3.3

[a] For 85 kW h battery.
[b] Battery final state of charge limited.

Taking into account these advantages, governments of different countries are encouraging the purchase of electric vehicles by subsidizing or financing them and implementing other actions, such as: tax exemption, tax deductions, transit and parking facilities, etc. Furthermore, some countries have established, or are in the process of establishing, limits on pollutant emissions for light vehicles. These countries are, among others, Australia, Canada, China, European Union, Japan, South Korea and U.S.A. [5,6]. To adapt their vehicles to these new regulations, automobile manufacturers have reduced emissions of ICEV and are developing new electric drive vehicles (Table 1). Thus, strong annual sales growth of PEVs is expected over the coming years, being possible to reach one million of units sold globally in 2017 [7].

PEVs are powered by electric batteries. Battery capacity of such vehicles are typically between 5–15 kW h for PHEVs and 25–40 kW h for BEVs [8]. The charge of such PEVs can be classified into three groups, depending on the charge power:

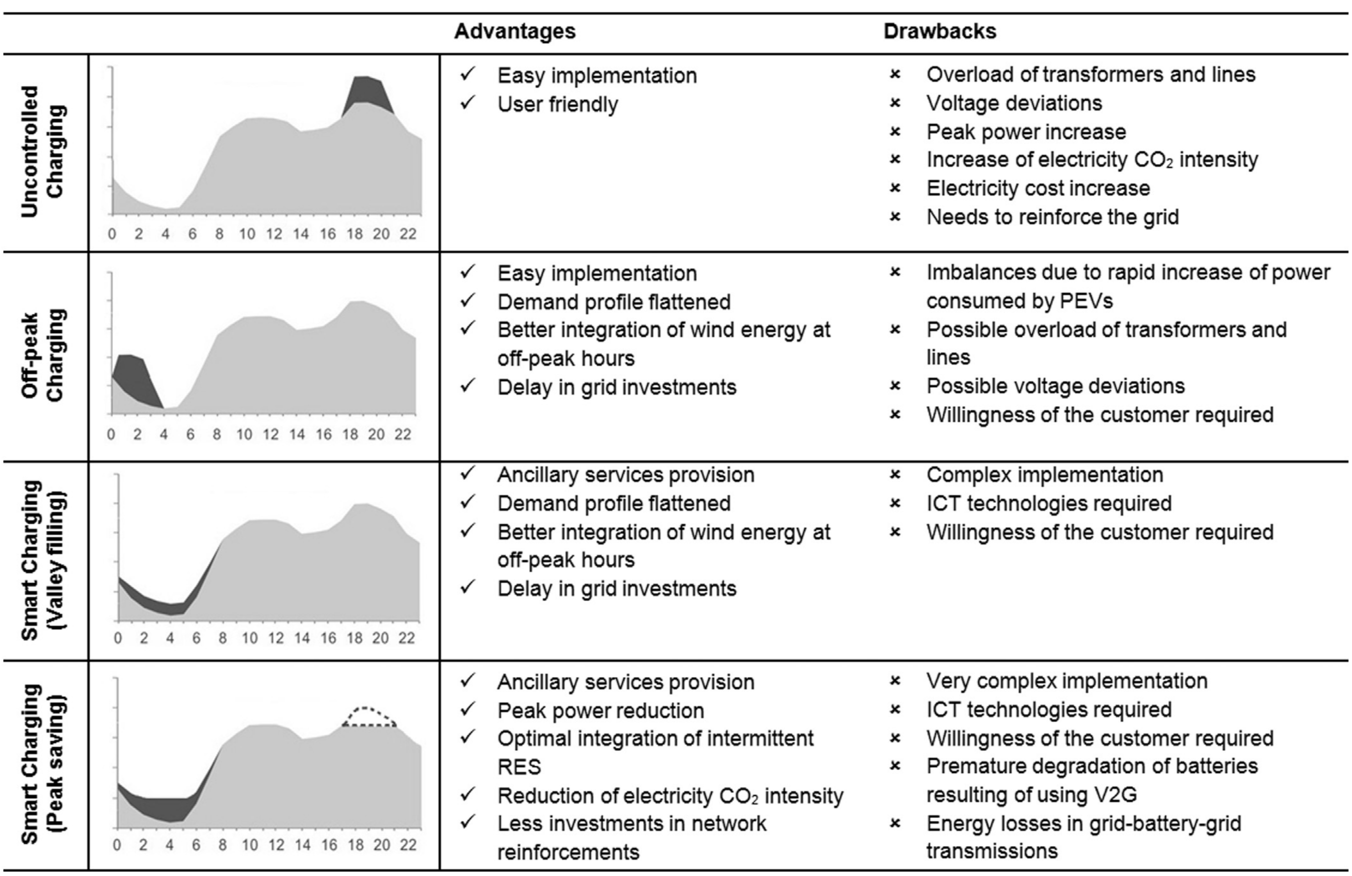

Fig. 1. Advantages and drawbacks of the different PEV integration approaches.

- Slow charging (1-AC): It is made in standard plugs; therefore, the charging power varies from country to country. In most European countries this power reaches 3.7 kW, i.e. 230 V and 16 A. However, there are other European countries with less power such as UK (230 V and 13 A) and Switzerland (230 V and 10 A).
- Fast charging (3-AC): In this case, charging power exceeds of a standard plug, but may be available in residential or commercial areas. Three-phase distribution systems are used and the charge power available depends on the distribution system in each country, around 10–20 kW.
- Ultrafast charging (3-AC or DC): This type of charging is performed using external chargers, due to the charger size and cooling requirements of the electronics integrated. The charging power can reach 50 kW or more. Ultrafast charging is commonly used by drivers to increase autonomy in transit or in emergencies. In both cases, time factor is important.

Considering the three options listed, the charging of large amounts of PEVs could cause multiple problems for electrical networks, such as: voltage deviations, quality of supply degradation, power losses increase, transformers and lines overloads, harmonics and fault currents increase [9–11]. It is estimated that the energy demand of 30 million PEVs may require about 100 TW h per day and an additional power of 35 GW [12]. Therefore, the smart integration of PEVs into electric grids is, together with the development of better and more efficient batteries, one of the biggest challenges of electric mobility technology.

At present, due to the poor penetration of PEVs, no integration strategy is performed (dumb or uncontrolled charging) or a passive strategy is implemented. Among passive strategies, the most widely used is the off-peak charging that encourages economically the charging of PEVs during night. However, this solution has the drawback of producing sudden power demand increases because all PEVs charging processes would begin almost simultaneously [13].

Therefore, as PEVs penetration in the market increases, it will be necessary to develop an active strategy or smart charging, which manages the charging of PEVs in an efficient way, and prevent or delay investments in reinforcing the grid. Besides, it must allow another objectives such as minimizing transmission losses and improving the integration of RES [14]. According to these strategies and from the point of view of the network, a PEV can be considered as: a simple electrical load (uncontrolled and off-peak charging cases); a flexible electrical load (smart charging valley-filling case) or a distributed and mobile storage element (smart saving-peak charging case). In all cases, depending on the control strategy used (Fig. 1).

Additionally, PEVs will have to share space with the Distributed Generation (DG) in low voltage distribution networks, causing impacts on the grid [15,16]. However, this pairing can produce some synergies which must be developed in order to improve the competitiveness of both technologies.

Researching how PEVs have to be controlled, in a smart way, can be a very complex task considering the large number of variables that come into play. Thus, several papers have been conducted regarding the plug-in electric vehicles and their integration into the grid. Some of the most recent and relevant work related to the topic is summarized below.

A brief review of PEVs components and technological challenges, related to energy storage system, motor drives and power electronics that have to be addressed, is carried out in [17]. PEVs will be a significant load to the grid and some papers have focused on the impacts that will produce in distribution networks. Authors in [18] give a survey about these studies, without obtaining specific conclusions about optimal charging strategies. Also, in [19] grid impact is reviewed, as well as economic and environmental impacts. On this last point, GHG emissions that PEVs can originate depend on electricity mix and driving patterns which are studied in [20,21], respectively. The impact that charging strategies can have on battery degradation is analyzed in [22]. Moreover, one of the key factors to know the effects that PEVs will have on the electric grid is estimating their market penetration. A comprehensive summary of PEVs penetration rate studies and their methods is presented in [23]. Besides, in order to control a great number of PEVs, an intermediate entity may be necessary. The aggregator agent will perform such function, making possible technical and economic management of PEVs. A literature survey about this aspect is done in [24], while in [25] economic dispatch strategies and risk management of PEVs is discussed. Different approaches for the integration of electric vehicles into power systems and smart grids is presented in [26].

Additionally, vehicle to grid (V2G) concept is one of the most promising developments to integrate efficiently PEVs. Nowadays is not clear that V2G technology is profitable. Such topic, as well as technologies, benefits and challenges are discussed in [27–30]. Also, the impact of V2G battery life is evaluated by authors of [31]. Role that can be played by plug-in electric vehicles, in order to allow more intermittent renewable generation in the grid, is surveyed in [19,32]. From the social point of view, adopting electric vehicles can be difficult, perhaps because of consumer aversion to new technologies. Benefits and barriers of PEVs and V2G technologies are analyzed in [33], charging behaviour of PEV users in [34] and attitudes and perceptions of consumers and early adopters towards electric vehicles in [35].

The objective of this paper is to review the aims proposed, strategies and tools used by different authors about this topic. Thereby, the researcher interested in this topic can get a picture of the state of the art and identify possible lines of research that are still uncovered. This paper is structured as follows. Section 2 introduces the smart charging concept and the two main control architectures of smart charging: centralized and decentralized control. Also, a comparison between them is performed. The role that PEVs can play, inside virtual power plants and microgrids, is presented in Section 3. Section 4 gives a brief overview of some existing PEVs projects around the world. Finally, Section 5 concludes by extracting some relevant findings as well as suggesting some recommendations for future work.

2. Smart charging of PEVs

Smart charging of PEVs allows customers and network operators to schedule PEVs charging profiles in order to get technical and economic benefits, being considered a specific demand side management (DSM) of PEVs. That is, smart charging seeks active control of loads and can be programmed with optimization or heuristic algorithms to achieve certain objectives, such as: avoid saturation of transformers and lines, reduce GHG emissions, minimize generation costs, etc.

There are two modes of operation between the PEV and the grid regarding energy flow direction. In charging mode, this direction is from the grid to vehicle (G2V) also known as unidirectional. Bidirectional is possible when power flow can go from vehicle to grid, also referred to as discharging mode. V2G concept can be considered as an extension of smart charging allowing PEVs to be able to inject energy into the grid, acting as distributed generators or storage systems [36]. This is possible because it is estimated that PEVs are parked 96% of the time [37]. Through V2G, PEVs can provide ancillary services (frequency control, load balance and spinning reserve services) [38,39]. It is believed that the use of such a system could be used for “valley

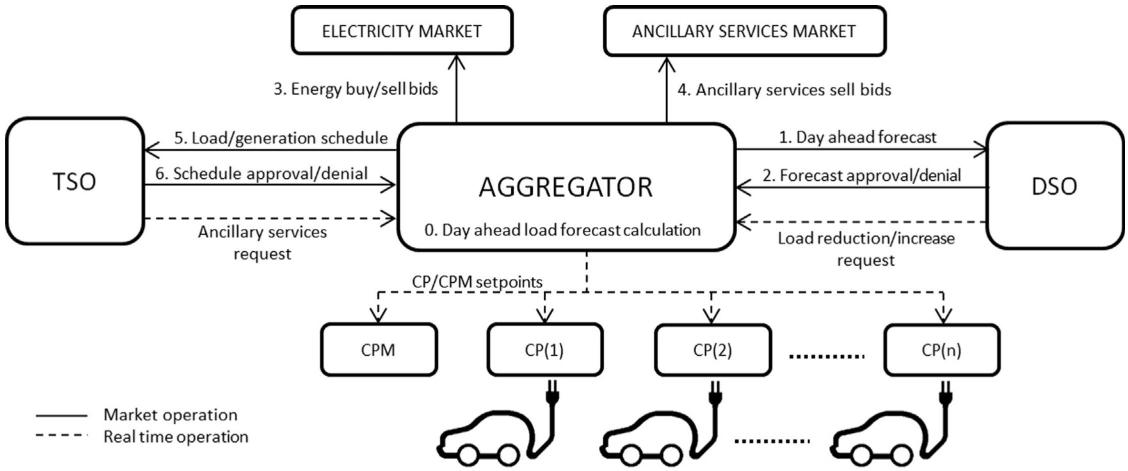

Fig. 2. Centralized control architecture proposed in [26,44].

filling" (timing devices to draw power at times of low grid demand) and "peak shaving" (reducing the peak energy demand on the grid). Moreover, both DSM and V2G can be an excellent tool to compensate for deviations caused by intermittent RES, such as wind power and solar photovoltaic [40–42]. However, main disadvantages of V2G are the premature degradation of batteries and energy losses during its operation.

Despite in the short/medium term is not expected that PEVs with V2G are enough competitive, taking into account battery degradation [43], it can be competitive in the provision of ancillary services [36]. Considering the long term, V2G may play a more important role as mass storage system, depending on the penetration of intermittent RES [37]. However, in order to make V2G concept possible, it is necessary to adapt electronic devices that act as interface between the PEV and the charging post (CP), to allow bidirectional exchange of energy.

Moreover, in order to make possible the technical and economic management or the coordination of PEVs charge, the existence of a new entity may be required. In many papers this entity is known as aggregator [24,44–46]. The aggregator function is to bind a significant amount of PEVs within a region and work as an interface between the different entities of the electrical system. The main objective is to give visibility to PEVs, both for technical management and for integration of these devices into the electricity market.

The control capacity of the aggregator will depend on the number of controllable PEVs connected and the flexibility provided by users of PEVs, depending on their preferences. These aspects will be defined by the initial charge level, the connection time and the desired final charge level. As the number of PEVs connected increases, more flexibility can be available for the aggregator in order to achieve its goals and improve the economic benefits.

Another source of income for the aggregator is the provision of ancillary services, such as primary and secondary frequency regulation, given the capacity of batteries of reducing/increasing electricity demand almost instantaneously [47]. As an example, it is estimated that the annual market of ancillary services in U.S.A. is 6.5 GW, with an estimated value in the range from 3 to 10 thousand million dollars [48].

Finally, the smart charging can be implemented in two different control architectures, centralized and decentralized controls. The aggregator functions vary according to the type of architecture. In some decentralized cases, aggregator functions may be assumed by the electricity retailer.

2.1. Centralized control architecture

Also known as direct control, the aggregator is responsible for managing directly the charge of all PEVs under its region (Fig. 2). Furthermore, the aggregator can control other entities, such as a charging post manager (CPM), which controls a group of PEVs in a car park.

The aggregator, in addition to the technical management, is also responsible for PEVs participation in the electricity market. Thus, it must perform daily demand forecasts based on historical data, user's preferences, etc. Once demand profile forecast of the whole controlled PEVs is obtained by the aggregator, this profile must be communicated to the Distribution System Operator (DSO) for prior approval. The DSO will check whether the profile compromises the safe operation of the distribution network. After receiving the approval of the DSO, the aggregator will perform the power purchase bids directly in the day-ahead market or through a utility. After market negotiation, the Transmission System Operator (TSO) will evaluate and will require changes in the demand profile, in case any problem could arise in the transmission network. If this technical assessment is positive, the aggregator will provide in real time the charging set-points to each connected PEV, in order to meet the commitments made in the electricity market.

In addition to the day-ahead market, the aggregator can also participate in the ancillary services market. The aggregator will estimate the ability to offer those additional services, such as secondary and tertiary frequency regulation. In case of being accepted, the aggregator will provide these services when TSO demands them.

If abnormal operation of the distribution system occurs, the aggregator, at the request of the DSO, will interrupt the operation of the system as scheduled by the market, and will perform the necessary corrective actions to return to safe operation of the distribution network. In this case, the aggregator will receive compensations stipulated by providing these services.

In real time operation, the aggregator must collect data from PEVs that are connected to the grid, such as PEV identification (ID), CP or CPM identification, state of charge of the batteries (SOC) and user's preferences. With this PEV ID, the aggregator may access these relevant data using databases (Fig. 3). Likewise, the CP ID provides extra data, as the location and the capacity of the CP.

With this information, the aggregator will apply algorithms to achieve the proposed objectives, while meets the needs of PEVs owners. In order to do so, all set-points will be sent to PEVs

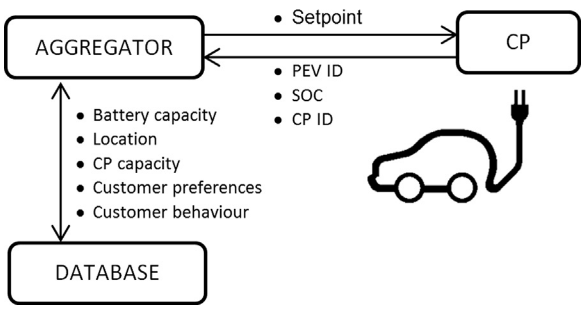

Fig. 3. Information required for aggregator operation.

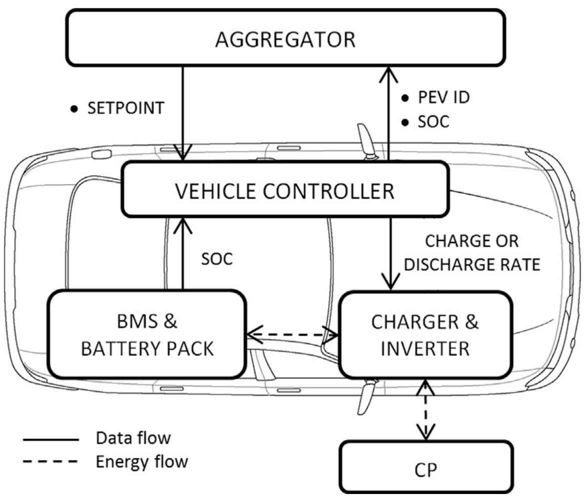

Fig. 4. Interactions between different elements in the centralized control.

through the CPs. Within each PEV, the control unit will receive the set-point and will act on the charger/inverter to set the required charge/discharge power (Fig. 4).

In the literature, a wide range of algorithms to achieve certain objectives can be found. Authors of [49] compare three optimized charging algorithms (named OptPrice, OptLoad and OptMaxReg) with their non-optimized versions. Their objectives are maximizing aggregator profits, in addition to improve costs for customer and limit grid impacts. Each algorithm depends on electricity prices, PEV load and ancillary services prices, respectively. Algorithms are simulated in Matlab using cvx tool, in order to solve convex optimization problems. Authors conclude that only optimized versions provide significant benefits to all players.

Focusing in market operation, it is important to minimize deviations between the demand profile expected by aggregator and the real time power demand of PEVs. In this aspect, Soares et al. give a linear optimal solution (convex optimization) in [50], which is suitable for quasi-real time application since its low computation time required. A heuristic method is also proposed based on power flow calculations, so as problematic feeders and buses can be identified. In this way, voltage and lines overloading problems could be solved.

Minimize generation costs is other objective for some authors. Valentine et al. [51] propose an intelligent charging algorithm to schedule PEV loads, in order to minimize stationary and ramping operation cost of generators. The optimization problem is solved with a meta-heuristic method (Simulated Annealing) and shows a cost reduction of 5–16%, compared with an uncontrolled scheme. In [52] an optimal dispatch of PEVs is performed in order to minimize overall system cost. The methodology proposed works as follows: batteries of PEVs at each network node are aggregated into a virtual storage resource, and then a multi-period optimal power flow (OPF) is carried out taking into account network constraints and PEV needs. In [53] a multi-objective scheduling strategy is formulated. In this paper, two different objective functions are presented: total operational cost and CO_2 emissions. Benders decomposition (convex optimization) is used to solve this large-scale problem. Then, a fuzzy solution is proposed to achieve the best compromise between the two objective functions. This way, both objectives can be enhanced.

Charging a large number of PEVs may produce transformer and lines congestion, power losses and voltage deviations. Therefore, this aspect is widely analyzed in the literature. In [44] a heuristic method is proposed to avoid overloads of lines and transformers, and improve voltage profiles, using an intelligent charging algorithm. Periodically, this algorithm calculates load flows and analyses whether the operating conditions are suitable. Otherwise, algorithm recognizes whether the problem is due to a voltage deviation in a node or to an overload of some element and proceeds to stop charging a percentage of PEVs, adding them to a waiting list. When the electrical network conditions allow it, the charge of the affected PEVs will be restarted. Other authors use Artificial Immune Systems algorithms (AIS) with a heuristic method [54]. Using AIS, authors seek the minimization of power losses while a heuristic method is implemented in order to avoid overloads and voltage limits violations. In this paper, IEEE 34 node test feeder is used to perform all simulations. In a similar way, a real-time coordination strategy of PEVs charging is presented in [55]. This strategy also combines a heuristic method with a function objective optimization, in this case with a maximum sensitivities selection (MSS) optimization. On the one hand, MSS optimization is used to calculate the impact that each PEV can have in the network power losses and then a charge priority is assigned to each PEV depending on this calculation. On the other hand, the heuristic method of this paper is designed to watch network constraints through performing power flows.

Minimize power losses is also the aim of [56]. Three optimal charging algorithms are developed and compared. First algorithm is designed to minimize power losses, second for minimize load variance and third for maximize load factor. The three algorithms achieve a reduction of power losses in the network, but load variance minimization is considered a good solution because it does not depended of the network topology. However, taking into account computation time, maximizing load factor is the best solution since it only requires half the time that load variance algorithm. It should be pointed out that computation time is a key factor to achieve real time solutions. At high penetration rates of PEVs, authors of [57] expose that computational complexity will be very high. In order to handle this problem, a double layer optimal charging strategy is proposed so as to minimize load variance. Algorithm to minimize load variance is also formulated in [58]. In this case, the objective is optimizing the energy consumption profile of a building. Authors use V2G concept to improve results. Two variants are proposed: a centralized approach and a decentralized approach. Regarding to the centralized approach, convex optimization is used to solve the algorithm. In contrast, authors of [59] use quadratic and dynamic programming in order to minimize power losses and voltage deviations. Researchers point out that quality of results obtained depends on the accuracy in forecasting the residential demand profile. The IEEE 34 node distribution test feeder is used for the analysis.

In several papers, only heuristic methods are used. Thus, in [60] three control strategies for flexible loads are compared: earliest deadline first (EDF), least laxity first (LLF) and receding horizon control (RHC). Authors consider that the control strategies RHC and EDF reduce the need for reserve capacity to cover non-dispatchable RES. In [61] a heuristic real time control with V2G is formulated. A priority of charging is assigned to each PEV

Table 2
Aspects analyzed in centralized control solutions.

Papers main objectives	**References**		**Solver/tools used**	**References**	
	No. V2G	**V2G**		**No. V2G**	**V2G**
Frequency regulation		[47,61]	Convex optimization	[49,50,52,56,63,64,66]	[53,65]
Voltage regulation		[62]	Quadratic optimization	[59,67]	
Minimize generation cost	[51,52,67]	[53]	Dynamic optimization	[59]	[47]
Reduce charging cost	[63,64]	[65]	Meta-heuristic method	[51]	
Maximize aggregator profits	[47,49,50]		Fuzzy logic		[53,62]
Reduce power losses	[54–56,59]		Artificial immune system	[54]	
Load levelling		[65]	Not specified		[57]
Maximize load factor	[56]	[61]			
Minimize load variance	[56]	[57,58]			
Avoid distribution network issues	[44,50,54,55,66]				
Reduce needs of spinning reserve	[60]				
Lower CO_2 emissions		[53]			
Strategy used	**References**		**Software used**	**References**	
	No. V2G	V2G		No. V2G	V2G
Function optimization	[49,51,52,56,59,63,64,66]	[47,57,58]	Matlab	[55,56,66]	[65]
			DigSilent PowerFactory	[66]	
Heuristic method	[44,60]	[61,62]	GAMS		[53]
Function optimization and heuristic method	[50,54,55]	[53]	Matlab/Matpower	[51]	
			PSS/E	[44]	

according to EDF policy. Authors also propose four different PEV charging modes in order to make feasible frequency regulation. Moreover, optimized dispatching with V2G often results in a quite complex problem. In [47] a dynamic programming algorithm is used to achieve an optimized frequency regulation with V2G. The aggregator should control the duration and rate of charging of each PEV in such a way that the revenue of participating in frequency regulation is maximized.

Additionally, considering that low voltage distribution networks have low X/R ratio, the reactive power control is inefficient to address voltage disturbances. Therefore, it is necessary to control the active power consumed by PEVs, in order to efficiently manage the voltage in such networks. This coordinated voltage control is complex when user's preferences are taken into account, since the coordinated control of voltage may cause delays in the charge process of PEVs. One solution to this problem is proposed in [62] using fuzzy logic to control flow energy between the grid and PEVs. The input variables of this control are the SOC of the battery and the measurement of local node voltage. With this method, voltage stability of the distribution network is improved and can be easily implemented in a real time scenario.

Some centralized approaches put the focus in reducing charging costs for the PEV customers. In [63] an objective function minimization of charging costs is presented. This function is divided in three parts: cost of purchasing electricity in spot market, cost of charging with downward reserve and positive income for having reserve capacity available. According to authors, an aggregator agent with an optimized bidding can reduce the charging costs in comparison to the dumb charging solutions. Also, participation in secondary downward reserve could be economically attractive. In the same line, [64] presents two optimized linear functions to use in aggregator entities. The first one is designed to calculate the amount of energy that has to be purchased by the aggregator in the day-ahead market. The purchased energy varies from 1 h to another, taking into account the electricity prices. The second one distributes that energy to the PEVs, with as little deviation from the schedule as possible. Another example of minimization of charge costs is proposed in [65], however this time V2G is available. Authors use model predictive control (MPC) to achieve valid solutions in compliance to IEC 61851, which defines that the charging power has to be semi-continuous, namely, charging power can be either zero or it ranges from a minimum positive value to a maximum positive value.

A summary of the analyzed centralized smart charging solutions can be found in Table 2.

To conclude this subsection, it should be noted that centralized control system presents several problems, due to the centralized nature of the data management. The first one is due to the importance of the aggregator for the system to function properly. Therefore, it is necessary to have a backup system to minimize the risk of a possible system failure. The second one is due to the amount of data that must be handled by the aggregator. As the number of PEVs increases, the amount of information that have to be transmitted and processed by the aggregator can be significant, making difficult to manage it and needing an expensive communications system. Finally, in this type of centralized control privacy issues can arise, because the aggregator will access to data from PEVs and, consequently, to transport habits of users.

Considering these aspects, it can be desirable to implement a decentralized control.

2.2. Decentralized control architecture

Also known as indirect, distributed or local control, the decision-making resides in each PEV, i.e. in each owner, rather than in an external entity as the aggregator (Fig. 5). This aspect implies that each PEV must have some intelligence.

Although the decision of "when and how much charge" is taken by the PEV itself, there are ways to influence these decisions, so that the charge of PEVs follows a pre-set criterion. This influence may come in the form of price or control signals that can be sent from an aggregator or directly from the utility. Thus, each PEV autonomously seeks to optimize the cost of charge, considering PEV user's preferences without sending sensitive private information to external entities.

If PEVs participate in electricity market, the mechanism would be similar to that described in the previous section. However, the aggregator or utility iteratively update price/control signals in order to modify the charging profile of PEVs.

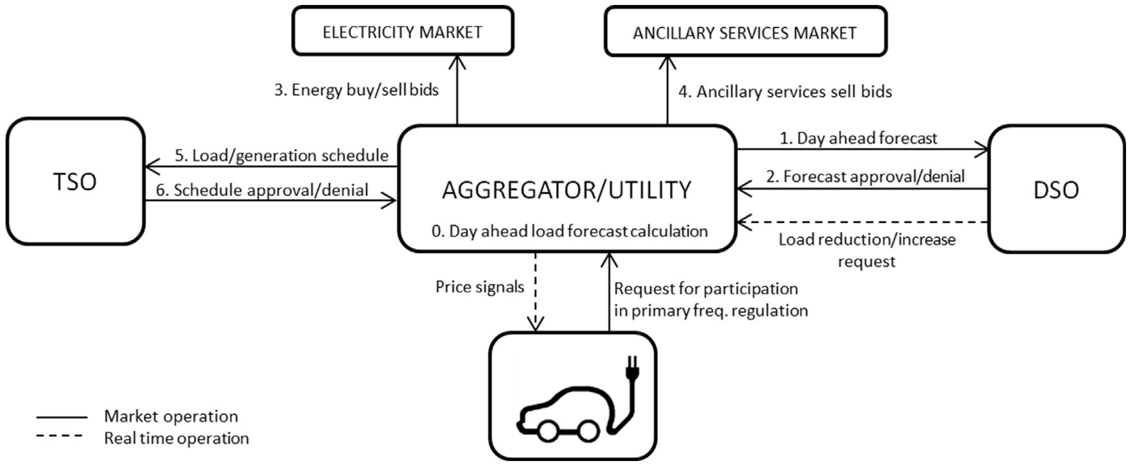

Fig. 5. Decentralized control architecture presented in [26].

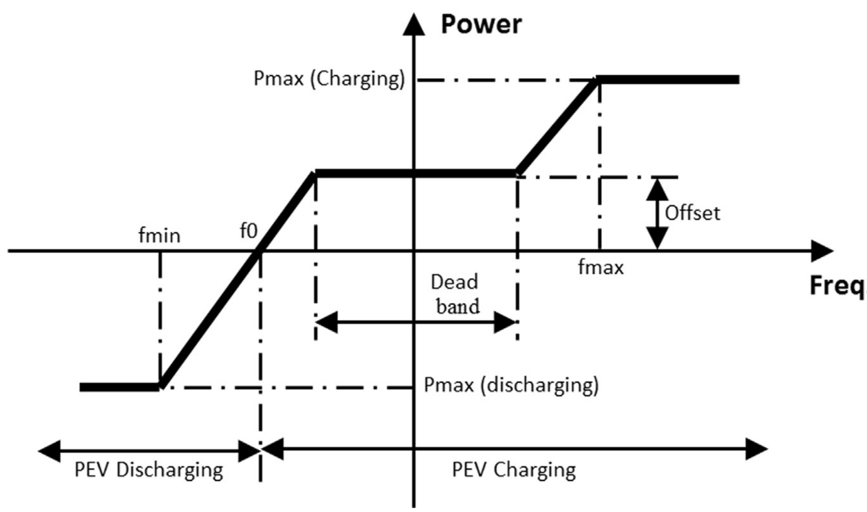

Fig. 6. Droop frequency control with V2G [42,74,75].

A large amount of papers that analyzed decentralized control put the focus in minimizing charging costs. In [58] the decentralized control version tries to minimize costs for users as well as decreases load variance using a non-cooperative game approach for a building. In this solution, each user receives data of the total load of the building from a building controller. Then, user finds the best optimized load profile in order to pay as less as possible. This profile is sent to the building controller which updates the total building load profile and sends it to another user. This procedure is done in rounds and repeated until convergence is reached. In a similar way, Gan et al. [68] propose an iterative algorithm that tries to fill the off-peak hours optimally. In each iteration, PEVs update their charging profile according to their own preferences and the control signal sent by the utility, which is updated until the control algorithm converges. To implement this solution, charging profile of each PEV must be communicated to the utility. Also, algorithm is adapted to track a predefined profile and for real time operation. In [69], an algorithm is formulated to minimize the overall charge cost of all PEVs using a game theoretic approach. Researches have taken into account the PEV owners' driving patterns, which have been obtained from statistical data of 2009 National Household Survey [70]. Additionally, a multi-level optimization to achieve valley-filling effect is implemented in [71], using price signals scheme. The pricing scheme is based on two convex optimization problems. At network level the objective is minimizing overall generating costs while at user lever is minimizing charging cost. Through signal prices, charging behaviour of PEVs can be altered indirectly.

However, this control scheme, aimed at cost optimization through price signals, has the drawback of being insensitive to several problems that may arise in certain points of the distribution network, as congestion of lines and transformers. Therefore, it is necessary to implement a control mechanism operated by the DSO that allows adjusting the charge set-point in abnormal situations. This control can be made through changes in price signal in the affected area, known as nodal prices strategy.

Moreover, provision of services such as secondary and tertiary frequency regulation are more complex due to the absence of a central system to coordinate the charging/discharging of PEVs. Instead, the primary frequency regulation and the voltage regulation are possible using the droop control methods (Fig. 6) to adjust PEVs charge power [42,72].

Normally, PEVs are individually connected in the low voltage networks. Therefore, it is more efficient to apply the active power control by reducing the power demand and even injecting power into the grid, in case the V2G option is available. To do this in a market environment, users must notify to the utility their intention to participate as a primary reserve. After communication has been established, the PEV will be designated as primary reserve supplier and the local control will be activated. When the

provision of this service is finished, the PEV will send a signal to the utility and will be compensated based on the time that has been available as primary reserve.

In this droop control, a dead zone has to be added, where PEVs do not respond to changes in frequency to ensure the longevity of batteries. This dead zone and the slope of the droop control should be defined according to the characteristics of the distribution network where PEVs are connected and take into account the willingness of users to participate in system frequency regulation. Furthermore, both absorption and power injection (only with V2G) should be limited by the battery and the charger characteristics. Finally, there must be an offset that represents the rated power consumption of PEVs when system is operating without frequency deviations.

Thus, for frequency deviations greater than the dead zone, PEVs' battery will respond as defined in droop control. If frequency decreases, the battery consumption will be reduced in the first instance. If still this action is not enough, the battery will start to inject power into the grid. Conversely, if frequency increases, the battery consumption will increase, in an attempt to drain the power excess in the system.

Many authors have used this classical technique of control. In [72] the droop control method is used to achieve suppression of frequency and voltage fluctuation, without using any type of communication. Possibilities of droop control to maximizes intermittent RES integration, using PEVs and V2G in islanded grids is researched in [42]. Also, in [73] V2G is used to provide frequency regulation in a islanded power system with high penetration of wind power sources. Two methods were tested, one based on droop controller and second one based on a PID controller. According to authors, on average 80% of frequency regulation reserves could be covered by PEVs with V2G. Simulations were performed in the DigSilent PowerFactory software. Geth et al. [75] propose an unidirectional (no V2G) droop method in order to limit under-voltage problems that can arise in distribution networks systems. Authors suggest that this droop method can have an impact in the charging rate of PEVs, in the worst case about 15%, while voltage deviations can be significantly improved in about 46%. Adaptive droop method can offer interesting solutions as in [74], where primary frequency control is performed while required charging level of customers is fulfilled.

A step forward may be to implement this droop technique as a part of a higher control, as Ahn et al. proposed in [76], where cost of generation and CO_2 emissions are minimized using linear programming and a droop control method is used for primary frequency regulation.

A drawback of these droop methods is that, from the standpoint of the network, the effective gain of this method is affected by the number of connected PEVs. Therefore, it is necessary that the control system updates the gain of the droop control of each PEV, which participate on the primary frequency/voltage regulation, to achieve a constant effective gain.

Also, implementation and organization of a decentralized control architecture, where intelligence is distributed in each PEV, can be performed using a tool known as multi-agent system (MAS) [77]. A multi-agent system is a set of two or more intelligent entities, named agents, which interact in an environment. The purpose of this tool is to reduce the complexity of a problem, by dividing it into sub-problems. According to Wooldridge [78], an agent is a virtual or physical entity located in an environment that is able to react autonomously to changes in that environment. The basic functions that define an agent are:

- *Autonomy.* Ability to meet designated targets without the constant guidance of a user.
- *Sensitivity.* Ability to perceive the environment and respond to changes.
- *Social ability.* Ability to interact with other virtual or physical agents.
- *Activeness.* Ability to take decisions and start their own actions to meet designated goals.

Agents can cooperate and communicate with each other, so that an agent may influence another agent's decisions and the state of their environment, in order to meet their needs and those of the system.

Each PEV will have its own agent, which will act in order to meet certain objectives, according to its status and environment. For instance, an agent can have the objective of charging with the minimum cost possible, while another agent may be programmed to have a minimum of SOC available, even whether it is penalized financially. Other types of agents can exists like transformer agent which may be responsible for prevent overloads.

Karfopoulos et al. [79], design and model a MAS method for charging PEVs. Each PEV agent tries to minimize charging cost. At the same time, a transformer agent can vary price signals of PEV agents in function of transformer loading. This way, overloading can be avoided. Optimization of charge of PEVs is solved by using a hybrid PSO technique while overall system is solved using a non-cooperative dynamic game. Authors suggest that with this solution an effective valley filling is achieved, minimizing energy losses. A real-time multi-agent system is carried out and demonstrated experimentally at laboratory scale in [80]. In this paper, four different agents are defined: DSO agent, coordinator agent, local area agent and PEV agent. The PEV agent sends PEV owner preferences and receives charging set-points from local area agent that had been previously calculated. Coordinator agent aggregates the demand of the local area agents and sends it to DSO agent which is responsible for the safely operation of distribution network. Local area agent calculates the charging profiles of each PEV in order to charging cost to be minimized. The experiments carried out by researches show that MAS can manages PEVs charging task avoiding overloads in distribution networks. Dallinger et al. [81] study the capability of PEVs in balancing the fluctuations generated by intermittent RES using an agent-based approach, V2G and price signals. Local optimization is carried out using a graph search algorithm taking into account variables such as prices, SOC, the available capacity, CP charging power, battery degradation and the beginning and end of the optimization. The local optimization algorithm goal is to minimize charging cost. A mechanism to avoid avalanche effects is also proposed in the paper. Avalanche effects are sudden increases of load demand or generation that may happen in decentralized price-signal approaches induced by optimal behaviour of PEVs, which tend to charge/discharge in time periods with the lowest/highest prices of electricity. A feedback of transformer loading is used to surpass the mentioned problem. Also, an approach to neutralize fluctuations of a wind farm is presented in [82], through congestion price signals, which is based on Internet traffic control. In this proposed solution, each PEV adjusts its charging set-point in function of the virtual market price (VMP) and the urgency level of the PEV. The VMP price reflects the difference between the wind power to be compensated and the aggregated PEV power. Instead, urgency level is an indicator of the charge margin of a particular PEV, considering variables like desired SOC and departure time. Authors suggest that their approach gives better frequency regulation than droop method and produces less battery degradation. Congestion pricing is also used in [83] to develop a distributed demand response algorithm with PEVs in a residential scenario. Price of energy in a certain period of time depends on the aggregated demand. Moreover, each user declares a price per time slot that he is willing to pay (WTP). Thereby, users who pay more receive a better quality of service, i.e. they will charge their PEVs in less time. As a

consequence of different WTPs between users, load levelling and peak saving can be achieved.

Another interesting approach to avoid network congestions, as well as voltage drops problems, is presented in [84]. Authors present a random access framework to schedule the PEVs charging. A network control centre will monitor load and voltage parameters of the different buses. When a PEV is plugged into a specific bus, a smart agent which makes decisions for the PEV will request data from control centre. The smart agent will schedule the PEV charging in function of two stochastic probabilities: access and suspend probability. The first one is designed to prevent the access to the network or resume the charging process, and the second one to suspend charging if any problem exists in the network. A mechanism is also added to assure that PEVs will reach the expected charging level before departure time is reached. In [85] a stochastic process is also used. Authors design a Markov chain not only to develop a smart charging system but also to model user driving patterns. This way, driving patterns are considered in the decision process that determines when a PEV has to be charged, in order to minimize charging costs. Besides, two versions are analyzed: unidirectional and bidirectional. Markov chain process is solved using a stochastic dynamic programming and, according to authors, it could achieve daily savings of approx. 19–47% in the G2V version, respect to dumb charging.

Decentralized voltage control is introduced in [86], using an iterative algorithm called best response dynamics (BRD) based on game theory. Authors use a sensitivity matrix to evaluate the alterations in voltage of pilot nodes induced by changes in active and reactive power injections. The solution procedure is as follows: all PEVs send to an aggregator their charging profile, the aggregator calculates the voltage on all the pilot nodes and sends back this information to each PEV. After that, each PEV updates its charging profile to minimize its objective function. Authors propose two objective functions, minimization of all pilot nodes of the analyzed network (global approach) or minimize only pilot nodes of its neighbourhood (local approach). Simulations are performed in the IEEE 34 distribution network model and show that there is little improvement respect to droop methods, as local and global approaches give similar results.

As discussed above, in a decentralized system the intelligence should go on board of the PEV, which means that there must be a dedicated hardware to process the data. The additional cost of this hardware can be avoided by using mobile agents. In the V2G concept, PEVs can be considered as distributed generation and distributed storage. But PEVs are also movable. Therefore, the distribution network where the PEV is connected demands nomadic computing capacity. This means that the PEV which is moving from an area to another one must be able to connect to different CPs and continue to experience the same level of quality of services and features, concept known as roaming. This concept requires that the PEV has the know-how of bidirectional power exchange with the network, the intelligence to make decisions based on the environment (SOC, market prices, system status, etc.) and an adequate computing power to run the required tasks. In other words, knowledge, intelligence and computing power must be on-board of the PEV.

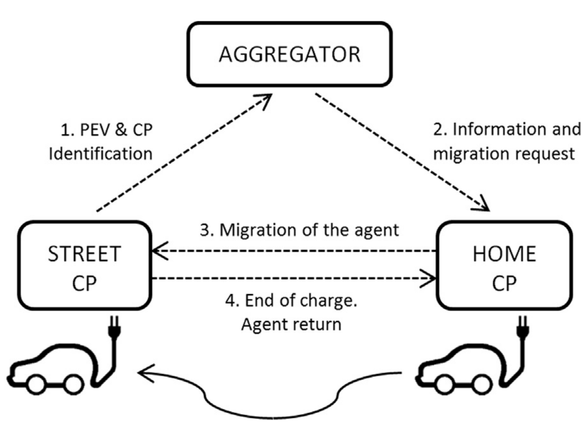

Fig. 7. Application of mobile agent concept for PEVs [88].

This requires the existence of an embedded system that allows the different charging strategies and market participation. But embedded systems usually have a limited computing power. In order to adapt this limited potential to V2G concept, embedded system should be improved, which will increase the cost of PEVs. That cost increase can be avoided by transferring the computing capacity to an external system using mobile agents concept [87], as shown in Fig. 7.

Thus, locally, there is an agent that is part of the residential energy management. This agent contains all the information and intelligence to control charging/discharging of PEVs batteries at local level. Once the PEV leaves the residential zone, the battery will discharge depending on the distance travelled, traffic and driving behaviour. In case that the battery SOC is greater than the travel needs of the user, and taking into account the possible degradation of the battery, the excess energy can be injected into the grid. To achieve a proper operation of V2G, intelligence and information data that reside on the stationary agent located in the residential environment is required. Therefore, a migration of information and intelligence to the new charging post is needed. The mobile agent technology allows this migration.

When the PEV is connected to the new charging post, an identification message is sent to the aggregator. This message contains the identity of the PEV and the location of the CP. After receiving this information, the aggregator sends the location of the CP to the stationary agent, which is cloned and migrated to the new CP. When this process is complete, the agent returns from the new CP to the residential CP and updates the data of the stationary agent. This system is only feasible if there is some kind of communications infrastructure that can be installed on each CP.

To finish this subsection, a summary of the analyzed decentralized smart charging solutions is presented in Table 3.

2.3. Comparison between centralized and decentralized control approaches

This subsection compares the intrinsic characteristics of the two control architectures presented. In this aspect, some authors have published papers using and comparing these two approaches. In [66], linear programming optimization is used in both architectures in order to charge PEVs within network constrains limits. Authors use Matlab to solve the optimization problem and the Digsilent PowerFactory software to test and compare the obtained solutions. The main conclusions obtained in the simulations are that centralized control approach makes a better use of the network capacity and achieves a better control of voltage, due to all network information is known by the central controller. However, centralized control approach needs a significant communication infrastructure.

Ref. [88] compares centralized charge management with MAS decentralized control approach. Authors note that centralized control is fairly impractical due to two factors, namely: requires accurate information about the user behaviour and its poor scalability. Moreover, decentralized control does not suffer from these defects and can provide valid solutions. In fact, authors point out that the decentralized solution is slightly dependent on the number of PEVs in the system because of its good scalability.

Authors of [52] formulate and contrast three different control systems: centralized control, decentralized with system-wide price signals and decentralized with nodal price signals. These

Table 3
Aspects analyzed in decentralized control solutions.

Papers main objectives	**References**		**Solver/tools used**	**References**	
	No. V2G	**V2G**		**No. V2G**	**V2G**
Frequency regulation	[77]	[42,72–74,82]	Convex optimization	[66,68,71,76]	
Voltage regulation	[76,87]	[72]	Dynamic optimization		[86]
Minimize generation cost	[52,71,77]		Game theory	[69,80,84,87]	[58]
Reduce charging cost	[52,68,69,80,81,84,86]	[58,86]	Genetic algorithm	[52]	
Provide ancillary services	[81]		Particle swarm opt.	[80]	
Reduce power losses	[80]		Graph search algorithm		[82]
Renewable integration		[42,82,83]			
Maximize load factor	[68,80]				
Minimize load variance	[71]	[58]			
Avoid distribution network issues	[66,84,85]	[89]			
Strategy used	**References**		**Software used**	**References**	
	No. V2G	**V2G**		**No. V2G**	**V2G**
Objective function optimization	[66,69,87]		Matlab	[66,76,77,84]	
Price signals	[52,71,80,81]	[58,82]	Matlab/Simulink	[71]	[42,72,75]
Control signals	[68,77]		Digsilent PowerFactory	[66]	[74]
Congestion pricing	[84]	[83]	JADE (Java)	[80,81,88]	[89]
MAS	[80,81]	[82,89]	PowerACE		[82]
Markov chains		[86]			
Droop method	[76,77]	[42,72,74]			
Stochastic algorithm	[85]				
Adaptive droop method		[75]			

Table 4
Characteristics summary of both control architectures.

	Advantages	**Drawbacks**
Centralized control	• Well known architecture • Better utilization of network capacity • Better ancillary services provision	• A complex and expensive communication infrastructure is required • A central controller and a backup of it is necessary • Complexity increases with the number of PEVs • Large amount of data to process • Possible privacy violations
Decentralized control	• Scalable • Improved fault tolerance • Less communications infrastructure required • Charge control remain in the user • Higher consumer acceptance	• Uncertainty in the final result • Limited ancillary services provision • Necessity of predicting or forecasting the reaction of consumers • Avalanche effects or simultaneous reactions may happen

control approaches are designed to optimize generating costs, whereas local network constraints are ignored. Simulations results show that the best solution, in terms of cost, is achieved with centralized control approach. However, decentralized control with nodal prices obtains similar results. Therefore, researches prefer the decentralized control approach taking into account that it presents better consumer acceptance and require less communications.

Thus, a comparison of different aspects of these two control schemes and a set of advantages and drawbacks of each approach (Table 4) can be found below:

- *Optimization*. In centralized control, application of optimization algorithms for PEVs charging is easier, since all system information is available at the same point. This aspect facilitates the management of distribution network, maximizing the network capacity utilization and the provision of supplementary services. However, in turn, it requires a large amount of data such as: desired final level of SOC, charging time available, battery capacity, etc. to reach the optimal solution. In practice, some of these data will be difficult to know in advance, therefore, the final solution will be affected. In the decentralized option, the global optimization is achieved through the influence of price or control signals over the PEV. However, the last decision is taken by each PEV, which implies that there is also some uncertainty in the final result. Also, avalanche effects may occur, that is, a huge number of PEVs can change their charge rate at the same moment in response to a significant fall/rise of electricity prices.
- *Information, communication and processing*. In the centralized architecture the information is received and processed at a central point. This will be computationally-intensive depending on the number of PEVs and the optimization algorithm applied. In contrast, in the distributed architecture, the information is processed in a distributed way; therefore, the requests for information, communication infrastructure and the data processing will be reduced. However, an on-board control unit is required in each PEV.
- *Privacy*. In the centralized control, privacy problems may exist because a third party will hold data about the PEVs user behaviour. This problem does not occur in decentralized control because the information is locally processed.
- *Modularity*. In centralized control, introduction of new PEVs into the system may require small changes in the control program of the aggregator. In principle, in the decentralized case, no changes are required.

- *Fault tolerance.* The centralized control architecture is more sensitive to errors, especially when occurring in the central management entity; therefore, a backup system is necessary.

3. Distributed generation and plug-in electric vehicles

In the last decade, the growth of distributed generation (DG) and renewable energy resources (RES) connected in low voltage networks has been remarkable, mainly due to environmental, commercial and regulatory aspects [89]. As an example, European Union countries have set a target of 20% RES by 2020 [90]. Therefore, these technologies are expected to become more profitable each time. However, as PEVs, DGs do not have the minimum size to compete in the electricity market under the same conditions than conventional generation. One solution may be to group PEVs and DGs, giving the visibility needed for intelligent control of these systems. Currently, there are two solutions to integrate actively DG and PEVs within the electrical system, the virtual power plants (VPPs) and the microgrids (MGs) [91].

3.1. VPP and PEVs

VPPs can be defined as a clustering model that tries to manage the electrical generation and demand, geographically dispersed, as if they were a single entity for the system operator (Fig. 8) [91–93]. Thus, a VPP has the advantage of reducing the financial risk regarding the individual participation of each distributed generator. In the future, it is expected that the VPP concept will maximize the benefits for distributed generators owners and the system operator.

Within a VPP, PEVs may be considered as mobile distributed energy sources that have the potential to provide advantages in the power system. The main advantages are the absence of "on and off" costs, very fast response time, low cost in standby and high availability factors [47,94]. Furthermore, the combination of VPP, RES and PEVs offers significant synergies that can allow an important reduction of CO_2 emissions [95,96].

VPPs with PEVs appear shortly in the literature, but it should be taken into account that the aggregator concept can be considered as a specific VPP for PEVs. Having said that, Raab et al. present possible control architectures for VPPs with PEVs [97]. Authors classify control systems into three types: direct, hierarchical and distributed control. They also note that in a VPP, mixed control modules or specific modules can exist for each DG technology. In the latter case, there is a specific module for PEVs group control, associated with that VPP, which authors refer to as EV management module. Besides, the control of a significant amount of PEVs and geographically distributed DGs can be expensive and complex. In [98], the architecture and communications system necessary for a centralized hierarchical control of a VPP with PEVs is discussed. Authors highlight the similarities that VPP-PEVs communication presents to that used in instant messaging and voice over IP, both protocols heavily used in telephony applications.

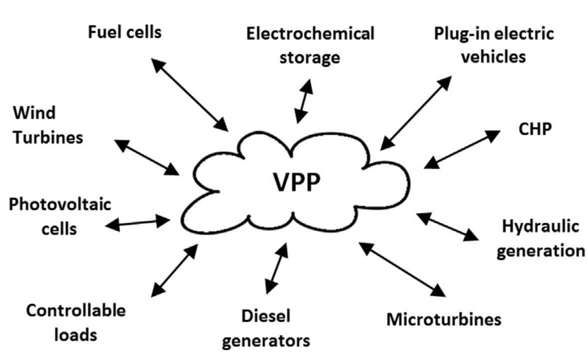

Fig. 8. Technologies that can be integrated into a VPP.

Authors of [99] propose creating agent-based VPPs composed of wind generation and PEVs in order to address the intermittent character of wind power generation. According to these authors, wind generators may use the available capacity of the PEV batteries to store energy when the electricity price is low and sell part of this energy when the price is high. In authors' approach, payment for PEV storage service is provided in form of charging entitlements rather than money, to take advantage of the price differential between wholesale market and retail market. Two optimization problems are solved: day-ahead optimization with the objective of maximize VPPs profits and receding horizon optimization to cope with changes in scheduled wind power generation.

Skarvelis-Kazakos et al. propose in [96] an optimization method to minimize CO_2 gas emissions of the VPP. Authors use a multi-time period optimization similar to economic dispatch but instead of use part-load cost curves, part-load CO_2 emissions curves are used.

3.2. Microgrids and PEVs

The microgrid concept was first introduced in 1998 as a set of micro-generators and electrical storage devices that are able to work isolated from the grid [100]. Subsequently, the Consortium for Electric Reliability Technology Solutions (CERTS) defines a microgrid as a set of loads and micro-generators operating as a single system, which provides both electrical and heat energy [101].

In the European Union, the microgrid concept was developed in the project "MICROGRIDS—Large Scale Integration of Micro-Generation to Low Voltage Grids". In this project, MGs are defined as a low-voltage (LV) distribution system, on a modular basis, where small power generators with electric loads are associated. In addition, electrical MGs may also contain electric storage devices, controllable loads, communication and management devices and cogeneration plants (CHP) [102].

Unlike VPPs, equipments that composed an electrical MG are geographically close to each other and can be operated isolated from the rest of the grid. In this way, the security of electricity supply to loads integrated within the MG is increased.

Several authors have analyzed how to integrate PEVs within a MG. In [44,87] an architecture for the management of PEVs in a microgrid is described (Fig. 9). In this case, the element called microgrid central controller (MGCC) is responsible for the market participation of the microgrid, through the market operator (MO), to operate the microgrid in an optimal way. The vehicle controller (VC), the micro-source controller (MC) and the load controller (LC) are located at the field level. As in the VPP, the control system may be centralized or decentralized.

In [103] a centralized control architecture is used to integrate PEVs in MGs. Authors design an algorithm called optimal power

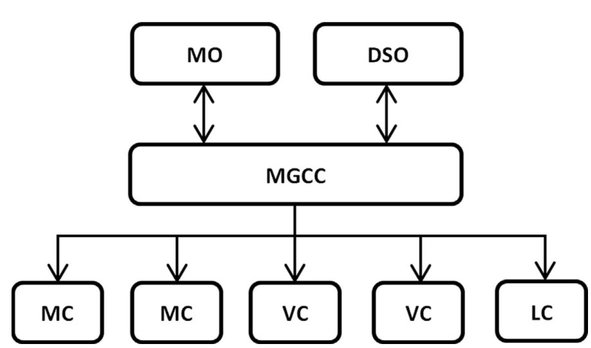

Fig. 9. Architecture of a microgrid with PEVs [44,88].

set-points calculator (OPSC) to minimize active power variance through the MV/LV substation. The OPSC calculates optimal load profiles for each PEV by using evolutionary particle swarm optimization tool, based on data such as battery technology, behaviour PEVs owners, mobility patterns, etc.

Two different control approaches are used in [104] to balance load and generation and compensate voltage unbalances in MGs using V2G. In the first one, local measurement of frequency and voltage are carried out to define two droop controls. Combination of these two droop controls is used to assign set-points to each PEV. In the second one, a central control device housed in the MGCC is implemented. MGCC measures the active power exchanges between the three phases and calculates the power set-points for each PEV connected in different phases in order to reduce phase unbalances in the MG.

Lopez et al. [105] propose a decentralized control operated with price signals based on multi-agent system. The objective of PEV users is maximizing the difference between incomings from energy sold (V2G) and the cost of energy bought. Authors introduce the technical agent, which takes care of doing optimal load flows in order to carry the MG to a state of optimal operation and technically feasible.

Decentralized MAS is also used in [106] to find optimal active power set-points for PEVs, distributed energy resources and loads. In the proposed system, PEVs agent transmits CP capacity, connection timer, initial and final SOC to the optimizing agent which runs an optimization routine based in artificial immune system (AIS). Once calculation is finished, optimizing agent sends the optimum set-points to each distributed energy resource, load and PEV. Authors of [107] present a strategy for congestion management in MGs with PEVs. This methodology is based on decentralized MAS architecture. Each agent solves an optimization problem to obtain the power dispatch needed to maximize its profits. After auction, a power flow and an optimal power flow are carried out to check whether the final situation is technically feasible, regarding overloaded lines. If it is not, for each overloaded line, the demand of specified nodes will be reduced or increased iteratively through changes in PEVs set-points, until congestion problem is surpassed.

4. PEV integration projects over the world

Several projects have been developed for the integration of electric vehicles into electrical grids (Table 5). These projects focus on three main aspects: the impact on the grid, the driving and charging behaviour of users, and the technical and economic integration of PEVs. Following the most relevant are summarized:

- *Grids for Vehicles (G4V)*. Formed by a consortium of 12 European entities, among which there were utilities (RWE, ENEL, EDF, etc.) and research institutions. The consortium aimed to explore the technical problems, the necessary regulation, business models and socio-environmental aspects, to make a set of recommendations for the implementation of EV in 2030 [108].
- *Mobile energy resources in grids of electricity (MERGE)*. European project centred in the management and control concepts to facilitate the massive integration of EVs in the electrical grid. The project also explored the possibilities of integrating PEVs in MGs and VPPs and the possible synergies with the smart metering systems [109].
- *EDISON project*. Funded by the Danish TSO Energinet.dk, focused on integrating PEVs and RES technologies using open standards of Information and Communication Technologies (ICT). The aim of the project was to develop infrastructure that enables EVs to intelligently communicate with the grid to determine when charging, and ultimately discharging, can take place. Also aimed to create a platform for testing and demonstration on the island of Bornholm [73,110].
- *SmartV2G project*. European project that aims connecting the electric vehicle to the grid by enabling controlled flow of energy and power through safe, secure, energy efficient and convenient transfer of electricity and data. Smart charging strategy is accomplished by a control system based on Model Predictive Control (MPC) theory, which optimally re-computes charge profiles for all the managed charging post each time a new recharge starts. It takes into account the current state of the grid, possible demand side management orders received in the charging post central controller by external agents (DSO or TSO) and the PEV users preferences (final cost, charging time) [111].
- *Green eMotion*. International project to coordinate different ongoing regional and national electromobility initiatives leveraging on the results and comparing the different technology approaches to promote the best solutions for the European market. It is composed by forty-three partners from industry, universities, research institutions, power supply companies and municipalities that have come together for the purpose of identifying the challenges of Europe-wide emissions-free transportation [112].
- *Mobincity: Smart mobility in smart city*. Related to integrate PEVs in smart cities, this project searches to define efficient and optimum charging strategies adapted to user and PEV needs and grid conditions [113].
- *EV project*. Launched in 2009 as the biggest initiative to introduce PEVs and CPs in U.S.A. This project was funded by the U.S.A. Department of Energy and several partners, such as Nissan and Chevrolet. The project has collected a lot of data to characterize the use of PEVs in different regions and climates. The effectiveness of charging infrastructure and possible business models have been evaluated for the implementation of public and commercial CPs. Until October 2012, the project had collected driving data corresponding to more than 64 million kilometres and logged more than one million charge events [114].
- *Vehicle-to-grid demonstration project*. This project aimed to demonstrate the feasibility and practicality of PEVs based grid regulation, and to assess the economic value based on real

Table 5
PEV grid integration projects.

Country/region	Project name	Project manager	Duration	State	Web page
European Union	G4V	RWE German utility	18 months	Finished	⟨http://www.g4v.eu/⟩
	MERGE	PCC Greek utility	24 months	Finished	⟨http://www.ev-merge.eu/⟩
	SmartV2G	ITE Spain R&D centre	36 months	Ongoing	⟨http://www.smartv2g.eu/⟩
	Mobincity	ITE Spain R&D centre	36 months	Ongoing	⟨http://www.mobincity.eu/⟩
	Green eMotion	Siemens	48 months	Ongoing	⟨http://www.greenemotion-project.eu/⟩
Denmark	EDISON	Danish Energy Association	24 months	Finished	⟨http://www.edison-net.dk/⟩
United States	EV project	ECOtality	48 months	Finished	⟨http://www.theevproject.com/⟩
	V2G Demonstration proj.	University of Delaware	Unknown	Finished	⟨http://www.udel.edu/V2G/⟩

operating data and real market prices for the service being provided [38].

5. Conclusions

Electric mobility is another step towards sustainability in modern society. Integration of PEVs in electrical distribution networks should be beneficial to all stakeholders, improving the efficiency of the system both technically and economically. In this context, smart charging is the key to achieve this ambitious objective. Two main architectures of smart charging can be found in the literature: centralized and decentralized control. Both can give valid solutions but at low penetration rates of PEVs, decentralized control scheme could be a good solution because of its low communications requirements. In contrast, in the long term and at high penetration rates of PEVs, centralized control architecture may be the best solution due to all network information is available at the same point. This way, distribution network capacity will be fully exploited. For the same reason, centralized control may be the most suitable for islanded grids. One of the main problems of centralized architecture is the necessity of communication infrastructure. However, in the future it is expected that almost every vehicle will be connected, so this aspect will not be a big problem.

Researches of this topic cover a wide range of objectives to implement a smart charging solution. Some of them use optimized methods to achieve the proposed objectives while others use heuristic methods. On the one hand, optimized methods are more used to maximize/minimize profits/costs. On the other hand, heuristic methods are more suited to keep distribution network within its operational limits. Moreover, optimized methods can achieve better solutions but they require more computation time, especially at high penetration rates of PEVs, which make them less suitable for real-time applications. A mix of both approaches may be a good solution where optimal algorithm is only calculated when specific events happen.

Primary voltage and frequency regulation may be done using droop control methods. Furthermore, droop control can be used in centralized and decentralized controls because it acts in different range of time. However, unless an adaptive droop control method is implemented, optimal frequency/voltage control is not obtained.

Integration of PEVs in MGs or VPPs have been less analyzed in the literature. Many papers about intelligent management of PEVs have been presented but only few of them have considered the integration of PEVs in MGs. The study of the ancillary services which PEVs could provide to the microgrid has not been completely researched.

Finally, active integration of PEVs can be a very complex task. In fact, many of the analyzed papers give solutions to technical or economic problems omitting other important issues such as voltage deviations, transformers overloading, etc. Additionally, many of the reviewed papers do not indicate the software used and very few authors use power system analysis software. As a consequence, it is more difficult to know which approaches are more suitable. Therefore, it would be desirable to address this problem from an overall perspective and using power systems simulation tools whenever possible.

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